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ANALOG CONVERTER

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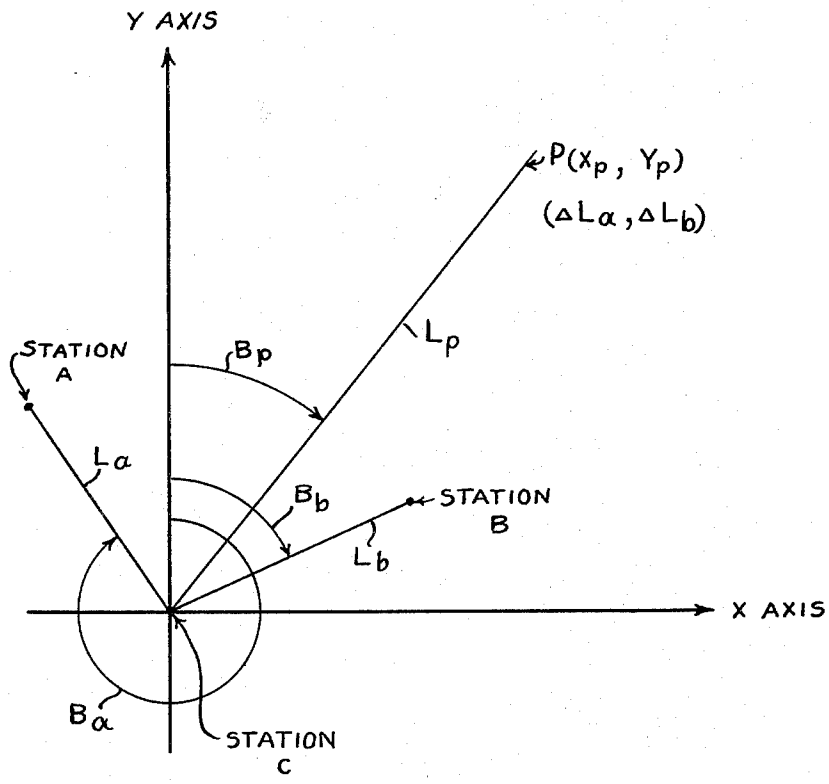


Fig. 1.

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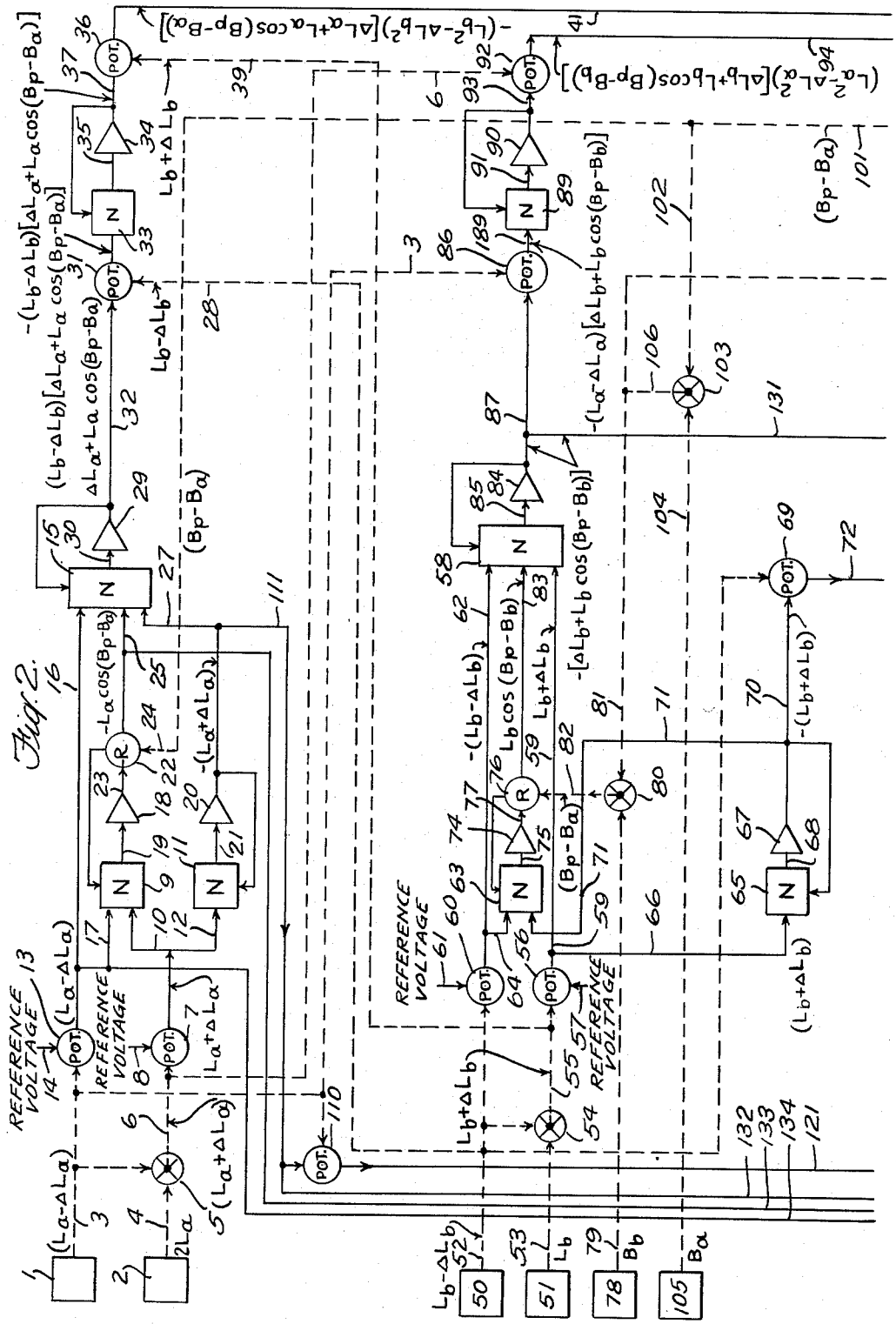
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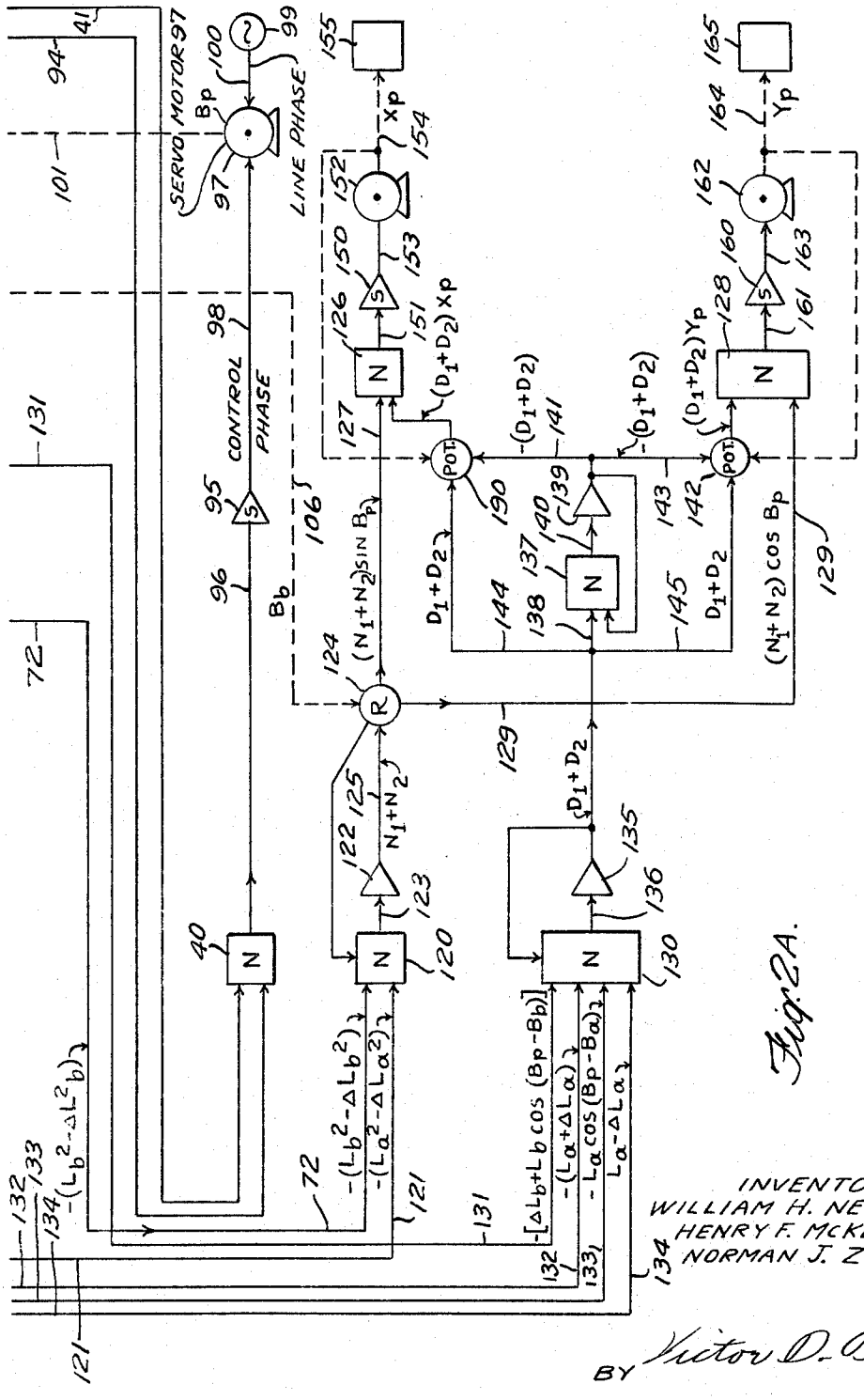


Fig. 2A.

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ANALOG CONVERTER

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3 Claims. (Cl. 235—187)

This invention relates to three-station navigational systems and has for its principal object that of providing an automatic device for accurately converting plane hyperbolic coordinates to plane rectangular coordinates.

Among conventional systems which provide plane hyperbolic coordinates of a position are three-station-radio-phase-comparison-systems for determining the geographic position of vehicles having an altitude small in comparison with its distance from the ground stations. Such vehicles may be ships, low, and moderately low, flying aircraft and guided missiles.

In the present state of the art, the conversion of plane hyperbolic coordinates to plane rectangular coordinates is laborious even with the aid of charts and maps. An automatic device which provides a virtually instantaneous conversion of the input data will have the following advantages: conservation of human resources, elimination of human error, continuous output data and the availability of solution quantities as rectangular coordinates in a physical analog form which are suitable for additional automatic computation. However, such an automatic device will have limited value and application unless it has a high order of precision.

In general, the invention contemplates analog instrumentation which responds to newly derived mathematics for the conversion of hyperbolic coordinates to plane rectangular coordinates and additionally, which reduces errors in the polar distance due to small unavoidable errors in polar bearing. The embodiments of the invention will comprise combinations of potentiometers, resolvers, adding networks, amplifiers and closed loop servomechanism systems.

The features of the invention will be understood more clearly from the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. 1 is a plane representation of a vehicle position relative to three reference station transmitters; and

FIGS. 2 and 2A are a schematic diagram of an analog device for automatically converting hyperbolic coordinates to rectangular coordinates.

Referring to the plane diagram in FIG. 1, point P is the location of a vehicle having plane hyperbolic coordinates ΔL_a and ΔL_b relative to transmitters located at three points A, C and B, the altitude of the vehicle being small compared to its distance from the points A, C and B. The point P has plane rectangular coordinates X_p along the X axis and Y_p along the Y axis in a system of convenient rectangular coordinates having its origin at the point C. The base line distance C to A is designated L_a and the base line distance C to B is designated L_b. The bearing of base line CA relative to the Y axis is designated B_a, the bearing of the base line CB relative to the Y axis is designated B_b, the bearing of the vehicle at P from the Y axis is designated B_p and its polar distance from the point C is designated L_p. The hyperbolic coordinates ΔL_a and ΔL_b are defined as (L_a-L_p) and (L_b-L_p), respectively, and these quantities are provided in the vehicle by a conventional arrangement of local receivers and phase comparators. From equipment located in the vehicle at the point P, the embodiments of this invention will continuously and automatically provide the rectangular coordinates X_p and Y_p for known input data of ΔL_a, ΔL_b, L_a, L_b, B_a and B_b.

For a three-station navigational system employing three ground station transmitters to provide hyperbolic coordinates of the relative vehicle position from local receivers and phase comparators, the mathematical conversion of plane hyperbolic coordinates to equivalent plane rectangular coordinates can be effected by the application of the following mathematically derived formulae:

$$L_p=\frac{L_a^2-\Delta L_b^2}{2[\Delta L_a+L_a\cos(B_p-B_a)]} \quad (1)$$

and;

$$L_p=\frac{L_b^2-\Delta L_b^2}{2[\Delta L_b+L_b\cos(B_p-B_b)]} \quad (2)$$

A simultaneous solution of the two formulae with known values of B_a, B_b, L_a, L_b, ΔL_a, and ΔL_b, will yield values of L_p and B_p. The plane rectangular coordinates X_p and Y_p of the vehicle relative to the central station can then be computed from the formulae:

$$X_p=L_p\sin B_p \quad (3)$$

$$Y_p=L_p\cos B_p \quad (4)$$

In the solution of Equations 1 and 2, the bearing B_p of the vehicle at point P is made available from the solution of the following equation:

$$\frac{L_a^2-\Delta L_a^2}{2[\Delta L_a+L_a\cos(B_p-B_a)]}=\frac{L_b^2-\Delta L_b^2}{2[\Delta L_a+L_a\cos(B_p-B_a)]} \quad (5)$$

It will be noted that after the value B_p is determined by equating Equations 1 and 2, the value L_p may be obtained from either Equation 1, Equation 2, or from some combination thereof. The method selected for determining L_p should be one which is comparatively insensitive to errors in B_p, the latter being unavoidably introduced during any physical calculation of B_p.

Specifically, for a good order of precision when a bearing error ΔB_p is unavoidably introduced, the resulting computed radial error

$$\frac{\partial L_p}{\partial B_p}\Delta B_p$$

(approximate) should not exceed the order of magnitude of the inherent tangential error $L_p\Delta B_p$ (approximate) so that the total error E as determined by:

$$E=\sqrt{\left(\frac{\partial L_p}{\partial B_p}\Delta B_p\right)^2+(L_p\Delta B_p)^2} \quad (6)$$

shall not greatly exceed the inherent tangential error.

The figure of merit which characterizes the accuracy of the calculation of L_p is defined by the quantity S which is equal to:

$$S=\frac{E}{L_p\Delta B_p} \quad (7)$$

From Equations 6 and 7, it can be seen that:

$$S=\sqrt{1+\left(\frac{1}{L_p}\cdot\frac{\partial L_p}{\partial B_p}\right)^2} \quad (8)$$

An analysis by partial differentiation of the Formulae 1 and 2 to provide, in each case, the radial sensitivity

$$\frac{\partial L_p}{\partial B_p}$$

indicates that for most of the expected configurations of the vehicle and the three stations, A, B and C, the radial error

$$\frac{\partial L_p}{\partial B_p}\Delta B_p$$

resulting from employing Formula 1 to obtain L_p is

approximately equal to and opposite in sign to the error resulting from employing Formula 2.

Hence, an improvement in the accuracy of the converter can be effected by determining L_p not from either Equation 1 or 2 alone, but instead from a combination of Equations 1 and 2 which tends to cancel out the radial error of each. This combination equation may be written as:

$$L_p=\frac{N_1+N_2}{D_1+D_2} \tag{9}$$

wherein, N_1, N_2, D_1, D_2 are respectively the numerators and denominators of Equations 1 and 2, i.e.,

$$N_1=L_a^2-\Delta L_a^2 \tag{10}$$

$$D_1=2[\Delta L_a+L_a \cos (B_p-B_a)] \tag{11}$$

$$N_2=L_b^2-\Delta L_b^2 \tag{12}$$

$$D_2=2[\Delta L_b+L_b \cos (B_p-B_b)] \tag{13}$$

Combining Equations 3, 4, and 9 yields

$$X_p=\frac{(N_1+N_2)}{(D_1+D_2)} \sin B_p=L_p \sin B_p \tag{14}$$

$$Y_p=\frac{(N_1+N_2)}{(D_1+D_2)} \cos B_p=L_p \cos B_p \tag{15}$$

For the above reasons, in the embodiments of this invention, an average will be effected of the numerators and denominators of Equations 1 and 2 as indicated by the Formulas 14 and 15 so as to compute L_p with a greatly reduced value of radial sensitivity. Such averaging introduces no new errors.

The error factor

$$\frac{1}{L_p}\frac{\partial L_p}{\partial B_p}$$

can be mathematically determined for the employed solution by taking partial derivatives of Equation 9, i.e.,

$$L_p=\frac{L_a^2-\Delta L_a^2+L_b^2-\Delta L_b^2}{2[\Delta L_a+L_a \cos (B_p-B_a)+\Delta L_b+L_b \cos (B_p-B_b)]} \tag{16}$$

thus;

$$\frac{\partial L_p}{\partial B_p}=\frac{(L_a^2-\Delta L_a^2+L_b^2-\Delta L_b^2) L_a \sin (B_p-B_a)+L_b \sin (B_p-B_b)}{2[\Delta L_a+L_a \cos (B_p-B_a)+\Delta L_b+L_b \cos (B_p-B_b)]^2} \tag{17}$$

From Equation 9:

$$\frac{2L_p^2}{L_a^2-\Delta L_a^2+L_b^2-\Delta L_b^2}=\frac{L_a^2-\Delta L_a^2+L_b^2-\Delta L_b^2}{2[\Delta L_a+L_a \cos (B_p-B_a)+\Delta L_b+L_b \cos (B_p-B_b)]^2} \tag{18}$$

Substituting in Equation 17 and dividing by L_p

$$\frac{1}{L_p}\frac{\partial L_p}{\partial B_p}=\frac{2L_p[L_a \sin (B_p-B_a)+L_b \sin (B_p-B_b)]}{L_a^2-\Delta L_a^2+L_b^2-\Delta L_b^2} \tag{19}$$

To demonstrate the reduced error consider a straight-line station configuration of points A, B and C, then

$$B_p-B_a=B_p-B_b\pm\pi \sin (B_p-B_a)=-\sin (B_p-B_b) \tag{20}$$

Hence for a straight line configuration, the formula becomes,

$$\frac{1}{L_p}\frac{\partial L_p}{\partial B_p}=(L_a-L_b)\left[\frac{2L_p \sin (B_p-B_a)}{L_a^2-\Delta L_a^2+L_b^2-\Delta L_b^2}\right] \tag{21}$$

Now, if $L_a=L_b$

$$\frac{1}{L_p}\frac{\partial L_p}{\partial B_p}=0$$

and,

$$S=\sqrt{1+\left(\frac{1}{L_p}\frac{\partial L_p}{\partial B_p}\right)^2}=1$$

Consequently, for nearly equal base lengths and an approximately straight-line station configuration, the total sensitivity S is of a very good order, that is, very near unity.

Referring to the analog coordinate converter of FIG. 2, driving devices **1** and **2** turn shafts **3** and **4** in direct proportion to input data $(L_a-\Delta L_a)$ and $2L_a$, respectively. Shafts **3** and **4** are connected to the two input shafts of a mechanical differential **5**. The differential output shaft **6** containing the information $(L_a+\Delta L_a)$ is connected to the shaft of a potentiometer **7** having a reference voltage input **8**. The output from the potentiometer **7** containing the information $(L_a+\Delta L_a)$ is connected to one of the two inputs of a adding network **9** by a cable **10** and to the input of a adding network **11** by a cable **12**, respectively. The shaft **3** is also connected to the shaft of a potentiometer **13** having an input reference voltage **14**. The output of the potentiometer **13** containing the information $(L_a-\Delta L_a)$ is connected to the first input of a three-input adding network **15** by a cable **16** and to the second input of the adding network **9** by a cable **17**. The output of the adding network **9** is connected to the input of an amplifier **18** by a cable **19** and the output of the network **11** is connected to an amplifier **20** by a cable **21**. The output of the amplifier **18** is connected to the input of a cosine resolver **22** by a cable **23** and the shaft of the resolver **22** is connected to a shaft **24** which is displaced in proportion to the quantity (B_p-B_a), the instrumentation for the shaft **24** being disclosed later. The output of resolver **22** containing the information $-L_a \cos (B_p-B_a)$ is connected to the second input of the adding network **15** by a cable **25**. A portion of the output of the resolver **22** is fed back to the network **9** for stabilization purposes. The output of the amplifier **20** containing the information $-(L_a+\Delta L_a)$ is connected to the third input of adding network **15** by a cable **27**. A portion of the output of the amplifier **20** is fed back to the adding network **11** for stabilization purposes. The output of adding network **15** is connected to the input of an amplifier **29** by a cable **30** and the output of the amplifier **29** containing the information $\Delta L_a+L_a \cos (B_p-B_a)$ is connected to the input of a potentiometer **31** by a cable **32**. A portion of the output of the amplifier **29** is fed back to the adding network **15** for stabilization purposes. The shaft of the potentiometer **31** is displaced by a shaft **28** in proportion to the quantity $(L_b-\Delta L_b)$, the instrumentation for the shaft **28** being disclosed later. The output of the potentiometer **31** containing the information

$$(L_b-\Delta L_b)[\Delta L_a+L_a \cos (B_p-B_a)]$$

is connected to the input of an amplifier **34** by a cable **35** and the output of the amplifier **34** containing the information $-(L_b-\Delta L_b)[\Delta L_a+L_a \cos (B_p-B_a)]$ is connected to the input of a potentiometer **36** by a cable **37**. A portion of the output of the amplifier **34** is fed back to the adding network **33** for stabilization purposes. The shaft of the potentiometer **36** is displaced by a shaft **39** in proportion to the quantity $(L_b+\Delta L_b)$, the instrumentation of the shaft **39** being disclosed later. The output of the potentiometer **36** containing the information

$$-(L_b^2-\Delta L_b^2)[\Delta L_a+L_a \cos (B_p-B_a)]$$

is connected to one input of a adding network **40** by a cable **41**.

Driving devices **50** and **51** turn shafts **52** and **53** in direct proportion to the input quantities $(L_b-\Delta L_b)$ and L_b respectively. The shafts **52** and **53** drive the two input shafts of a mechanical differential **54** and the differential output shaft **55** of the differential **54** containing the information $(L_b+\Delta L_b)$ drives the shaft **39** and the

shaft of the potentiometer **56**. Potentiometer **56** has a reference voltage input **57** and its output containing the information $(L_b+\Delta L_b)$ is connected to the first input of a three-input adding network **58** by a cable **59**. The shaft **52** is connected to the shaft **28** and connected to drive the shaft of a potentiometer **60** which has a reference voltage input **61**. The output of potentiometer **60** containing the information $-(L_b-\Delta L_b)$ is connected to the second input of the adding network **58** by a cable **62** and to one input of a two-input adding network **63** by a cable **64**. The output of potentiometer **56** containing the information $(L_b+\Delta L_b)$ is connected to the input of a adding network **65** by a cable **66** and the output of the adding network **65** is connected to the input of an amplifier **67** by a cable **68**. The output of the amplifier **67** containing the information $-(L_b+\Delta L_b)$ is connected to input of a potentiometer **69** by a cable **70** and to the other input of adding network **63** by a cable **71**. The shaft of the potentiometer **69** is driven by the shaft **52** and the output of potentiometer **69** in cable **72** contains the information $-(L_b^2-\Delta L_b^2)$. A portion of the output of the amplifier **67** is connected to the adding network **65** for stabilization purposes. The output of adding network **63** is connected to an amplifier **74** by a cable **75** and the output of the amplifier **74** is connected to the input of a cosine resolver **76** by a cable **77**. The amplitude of the quantity being resolved in the resolver **76** is fed back to the network **63**. A driving device **78** turns a shaft **79** in direct proportion to the input quantity B_b and the shaft **79** is connected to one input shaft of a differential **80**. The other input shaft to the differential **80** is connected to a shaft **81** which displaces in direct proportion to the quantity B_p, the instrumentation of the shaft **81** being disclosed later. The differential output shaft **82** of the differential **80** containing the information B_p-B_b is connected to the shaft of the resolver **76**. The output of the resolver **76** containing the information $L_b \cos (B_p-B_b)$ is connected to the third input of the adding network **58** by a cable **83**. The output of the adding network **58** is connected to the input of an amplifier **84** by a cable **85**. The output of amplifier **84** containing the information $[\Delta L_b+L_b \cos (B_p-B_b)]$ is connected to a potentiometer **86** by a cable **87** and the shaft of potentiometer **86** is driven by a connection to the shaft **3**. The output of amplifier **84** is fed back to the adding network **58** for nullification purposes. The output of potentiometer **86** containing the information

$$-(L_a-\Delta L)[\Delta L_b+L_b \cos (B_p-B_b)]$$

is connected to a adding network **89** by a cable **189**. The output of the adding network **89** is connected to the input of an amplifier **90** by a cable **91** and the output of the amplifier **90** containing the information

$$(L_a-\Delta L_a)[\Delta L_b+L_b \cos (B_p-B_b)]$$

is connected to the input of a potentiometer **92** by a cable **93**. A portion of the output of amplifier **90** is fed back to the network **89** for stabilization purposes. The shaft of the potentiometer **92** is connected to the shaft **6** containing the information $(L_a+\Delta L_a)$. The output of the potentiometer **92** containing the information

$$(L_a^2-\Delta L_a^2)[\Delta L_b+L_b \cos (B_p-B_b)]$$

is connected to the other input of the adding network **40** by a cable **94**. The output of the adding network **40** is connected to the input of a servo amplifier **95** by a cable **96** and the output of the servo amplifier **95** is connected to the control phase of a reversible two phase B_p servomotor **97** by a cable **98**. The line phase of the B_p servomotor **97** is connected to a single phase voltage source **99** by a cable **100**. The shaft **101** of the servomotor **97** is connected to the shaft **24** of the resolver **22** and to the input shaft **102** of a differential **103**. The other input to differential **103** is a shaft **104** which is turned by a driving device **105** in direct proportion to the input quantity B_a. The differential shaft **106** of the differential **103** is connected to the shaft **81**. The shaft **101** of the servomotor **97** will seek an equilibrium quiescent position until the two inputs to the network **40** total to zero. At such time, the shaft **101** will be displaced in direct proportion to the quantity (B_p-B_a) and the shafts **106** and **81** will be displaced in proportion to the quantity B_p.

The input of a potentiometer **110** is connected to the output of the amplifier **20** containing the information $-(L_a+\Delta L_a)$ by a cable **111**. The shaft of the potentiometer **110** is connected and driven by the shaft **3**. The output of the potentiometer **110** containing the information $-(L_a^2-\Delta L_a^2)$, which is equal to $-N$ by Equation 12, is connected to one input of an adding network **120** by a cable **121**. The other input to the adding network **120** is connected to the cable **72** containing the information $-(L_b^2-\Delta L_b^2)$, which is equal to $-N_2$ by Equation 14. The output of the adding network **120** is connected to the input of an amplifier **122** by a cable **123**. The output of the amplifier **122** containing the information (N_1+N_2) is connected to the input of a sine-cosine resolver **124** by a cable **125**, the shaft of the sine-cosine resolver **124** being driven by the shaft **106** containing the information B_p. One output of the resolver **124** containing the information $(N_1+N_2)\times(\sin B_p)$ is connected to one input of an adding network **126** by a cable **127** and the other output containing the information $(N_1+N_2)\cos B_p$ is connected to one input of an adding network **128** by a cable **129**. A portion of the output of the resolver **124** is fed back to the network **120** for stabilization purposes.

The output of the amplifier **84** containing the information $-[\Delta L_b+L_b \cos (B_p-B_b)]$ is connected to the first input of a four input adding network **130** by a cable **131**. The output of the amplifier **20** containing the information $-(L_a+\Delta L_a)$ is connected to the second input of the adding network **130** by a cable **132** connected to cable **111**. The output of the resolver **22** containing the information $-L_a \cos (B_p-B_a)$ is connected to the third input of network **130** by a cable **133**. The output of the potentiometer **13** containing the information $(L_a-\Delta L_a)$ is connected to the fourth input of adding network **130** by a cable **134**. The output of the adding network **130** is connected to an amplifier **135** by a cable **136**. The output of amplifier **135** containing the information $[\Delta L_a+L_a \cos (B_p-B_a)]+[\Delta L_b+L_b \cos (B_p-B_b)]$, which is equal to $\frac{1}{2}(D_1+D_2)$ by Equations 11 and 13, is connected to a network **137** by a cable **138**. A portion of the output of amplifier **135** is fed back to network **130** for stabilization purposes. The output of adding network **137** is connected to the input of an amplifier **139** by a cable **140** and the output of the amplifier **139** is connected to one input of a potentiometer **190** by a cable **141** and to one input of a potentiometer **142** by a cable **143**. A portion of the output of amplifier **139** is fed back to adding network **137** for stabilization purposes. The other input of potentiometer **190** is connected to the output of amplifier **135** by a cable **144** and the other input of the potentiometer **142** is connected to the output of amplifier **135** by a cable **145**. The output of potentiometer **190** is connected to the other input of the network **126** and the output of potentiometer **142** is connected to the other input of the network **128**. The differential output of network **126** is connected to a servo amplifier **150** by a cable **151** and the output of servoamplifier **150** is connected to a servomotor **152** by a cable **153**. The shaft **154** of the servomotor **152** is connected to drive an output device **155** and the shaft of the potentiometer **190**. The servomotor shaft **154** will seek an equilibrium position until the two inputs to the adding network **126** cancel each other. At the quiescent condition, the equation

$$X_p=\left(\frac{N_1+N_2}{D_1+D_2}\right)\sin B_p$$

will be satisfied and the servomotor shaft **154** will be displaced in direct proportion to the desired X_p quantity.

The output of adding network **128** is connected to a servo amplifier **160** by a cable **161** and the output of servoamplifier **160** is connected to a servomotor **162** by a cable **163**. The shaft **164** of the servomotor **162** is connected to drive an output device **165** and the shaft of the potentiometer **142**. The servomotor shaft **164** will seek an equlibrium position until the two inputs to the differential network **128** cancel each other. At the quiescent condition, the equation

$$Y_p=\left(\frac{N_1+N_2}{D_1+D_2}\right)\cos B_p$$

will be satisfied and the servomotor shaft **164** will be displaced in direct proportion to the desired Y_p quantity.

It is to be understood that various modifications of the invention other than those above described may be effected by persons skilled in the art without departing from the principle and scope of the invention as defined in the appended claims.

What is claimed is:

1. An analog computation device for converting phase hyperbolic coordinates to plane rectangular coordinates comprising means for continuously mechanizing and solving equations having the basic form:

$$X_p=\left(\frac{N_1+N_2}{D_1+D_2}\right)\sin B_p$$

and

$$Y_p=\left(\frac{N_1+N_2}{D_1+D_2}\right)\cos B_p$$

to obtain continuously the quantities X_p and Y_p which are related to: three reference points A, C and B having base lines L_a and L_b, L_a being measured from C to A and L_b being measured from C to B, a rectangular coordinate system having an X axis and a Y axis with their origin at the said point C, the bearing of the said base line L_a being B_a and the bearing of the said base line L_b being B_b as measured from the Y axis, and a point P having hyperbolic coordinates ΔL_a and ΔL_b relative to the said reference points A, C and B and rectangular coordinates X_p and Y_p relative to the said X and Y axes, the point P having a polar bearing B_p as measured from the Y axis, wherein N_1 is equal to the computation quantity $(L_a^2-\Delta L_a^2)$, N_2 is equal to the computation quantity $(L_b^2-\Delta L_b^2)$, D_1 is equal to the computation quantity $2[\Delta L_a+L_a\cos(B_p-B_a)]$ and D_2 is equal to the computation quantity $2[\Delta L_b+L_b\cos(B_p-B_b)]$ and the said means for mechanizing comprising means for continuously mechanizing and solving the said equations includes first means for generating quantities proportional to the observed quantities L_a, $(L_a-\Delta L_a)$, L_b and $(L_b-\Delta L_b)$, first means responsive to said generating means for computing the quantity (N_1+N_2), second means for generating quantities proportional to the observed quantities B_b and B_a, second means responsive to said first and second generating means for computing the quantity B_p, third means responsive to said first and second generating means and said second computing means for computing a quantity (D_1+D_2), resolving means connected to said

(N_1+N_2) and B_p computing means for obtaining a first resolved output quantity $(N_1+N_2)\sin B_p$ and a second resolved output quantity $(N_1+N_2)\cos B_p$, means connected to said resolving means to receive the first resolved output quantity and to said (D_1+D_2) computing means for obtaining the coordinate quantity X_p and means connected to said resolving means to receive the second resolved output quantity and to said (D_1+D_2) computing means for obtaining the coordinate quantity Y_p.

2. An analog computation device as claimed in claim 1 wherein the said means connected to said resolving means to receive the first resolved output quantity and to said (D_1+D_2) computation means for obtaining the coordinate quantity X_p includes a closed loop servomechanism system having a potentiometer connected to said (D_1+D_2) computing means, a differential network connected to the output side of said potentiometer and to said resolving means to receive the said first resolved output quantity, a servoamplifier driven by the output of the said differential network and an electric motor having an output shaft, said motor being driven by the servo amplifier and said output shaft being in driving connection with the said potentiometer, whereby the displacement of the motor shaft is directly proportional to the coordinate quantity X_p.

3. An analog computation device as claimed in claim 2 wherein the said means connected to said resolving means to receive the second resolved output quantity and to said (D_1+D_2) computation means for obtaining the coordinate quantity Y_p includes a second closed loop servomechanism system having a second potentiometer connected to said (D_1+D_2) computing means, a second differential network connected to the output side of said second potentiometer and to the said resolving means to receive the said second resolver output quantity, a second servoamplifier driven by the output of the said second differential network and a second electric motor having an output shaft said second motor being driven by the said second servoamplifier and the said output shaft of the said second motor being in driving connection with the said second potentiometer, whereby the displacement of the motor shaft is directly proportional to the coordinate quantity Y_p.

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